ANL/ESD-17/25

Summary of Expansions, Updates, and Results in GREET® 2017 Suite of Models

Energy Systems Division

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Summary of Expansions, Updates, and Results in GREET® 2017 Suite of Models

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1 INTRODUCTION

This report provides a technical summary of the expansions and updates to the 2017 release of Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) model, including references and links to key technical documents related to these expansions and updates. The GREET 2017 release includes an updated version of the GREET1 (the fuel-cycle GREET model) and GREET2 (the vehicle-cycle GREET model), both in the Microsoft Excel platform and in the GREET.net modeling platform. Figure 1 shows the structure of the GREET Excel modeling platform. The .net platform integrates all GREET modules together seamlessly.

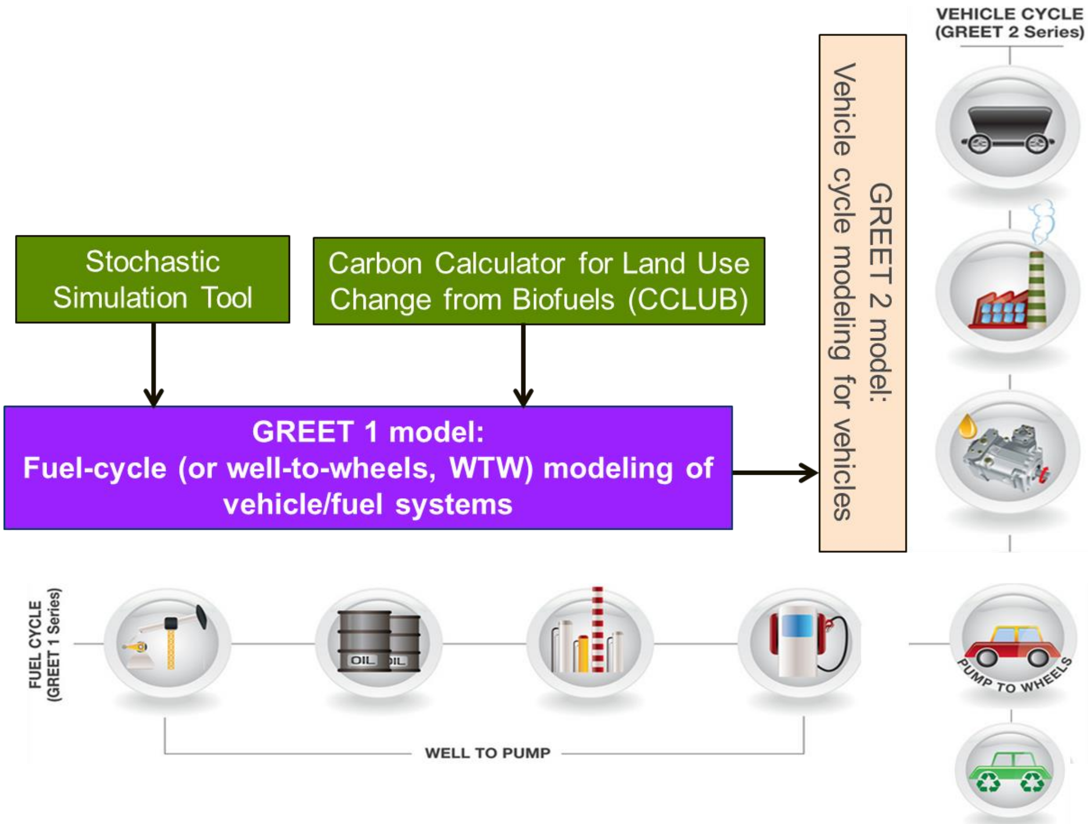

FIGURE 1 GREET Models as Configured in GREET Excel Modeling Platform

The report is organized in three sections: (1) GREET major expansions and updates, (2) GREET other updates, and (3) GREET results, as presented electronically in the GREET well-to-wheels (WTW) Calculator.

GREET includes life cycle analysis (LCA) for road transportation, air transportation, marine transportation, and rail transportation, as shown in FIGURE 2. The model includes more than 100 fuel/energy general production pathways from energy feedstocks to final energy productions, as shown in FIGURE 3. For each general pathway, there are multiple production and vehicle technology options, resulting more than 800 technology-specific fuel/vehicle pathways. FIGURE 4 presents the vehicle technologies for road transportation included in GREET.

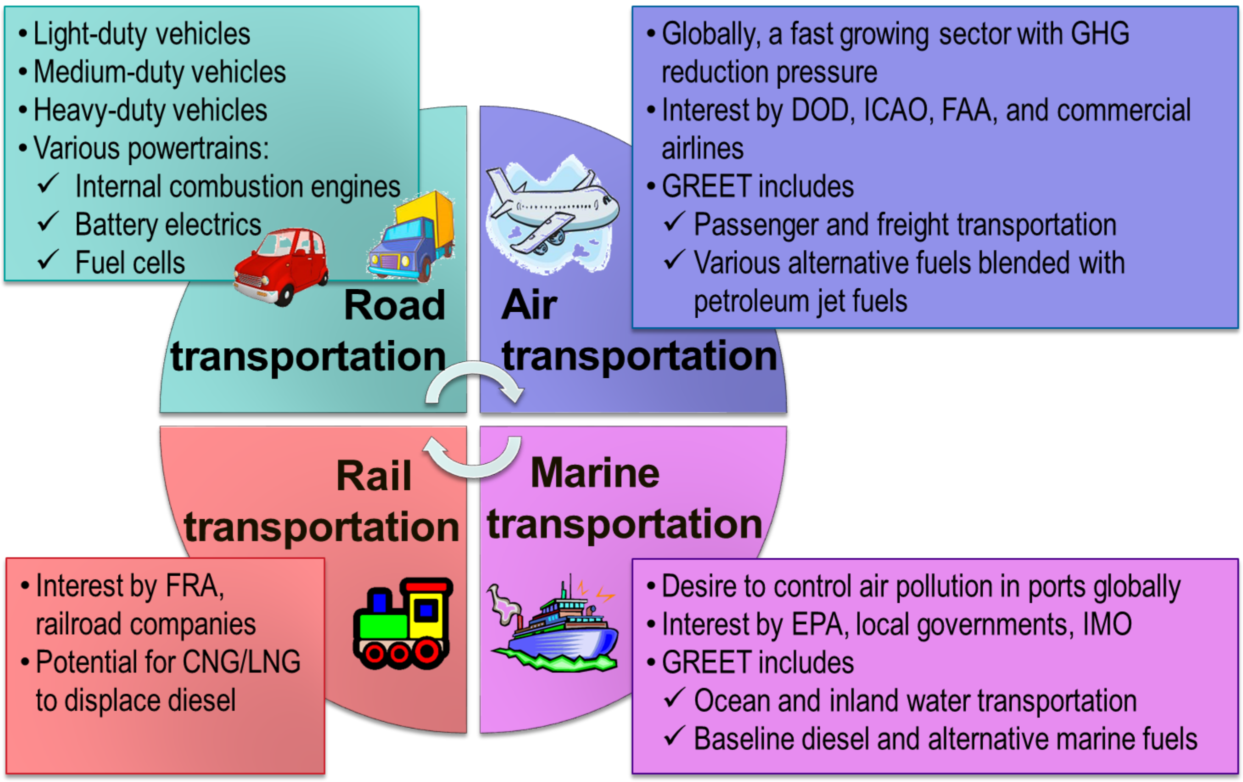

FIGURE 2 GREET Coverage of Transportation Sub-Sectors
(GHG: Greenhouse Gases; DOD: Department of Defense; ICAO: International Civil Aviation Organization; FAA: Federal Aviation Administration; CNG: Compressed Natural Gas; LNG: Liquefied Natural Gas; EPA: Environmental Protection Agency; IMO: International Maritime Organization)

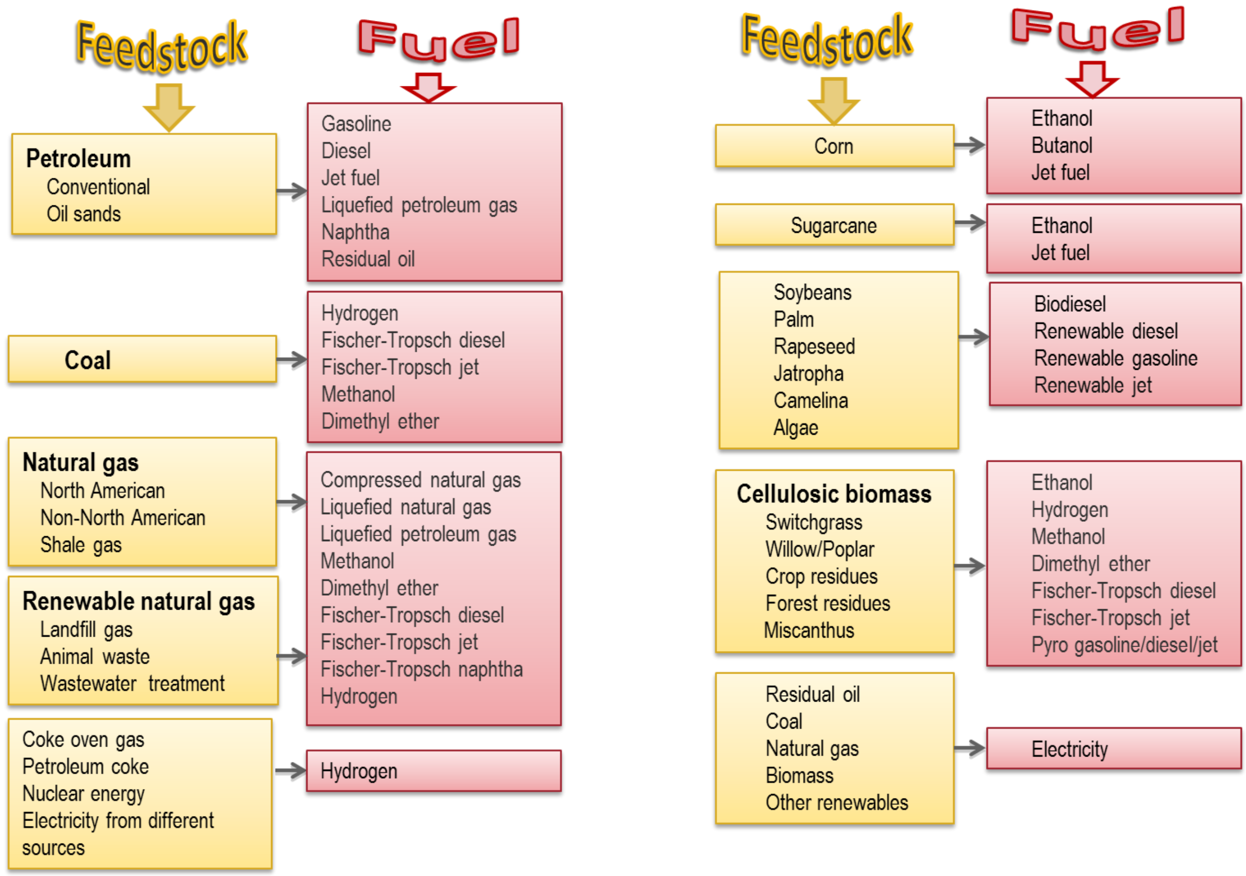

FIGURE 3 Fuel/Energy General Production Pathways in GREET

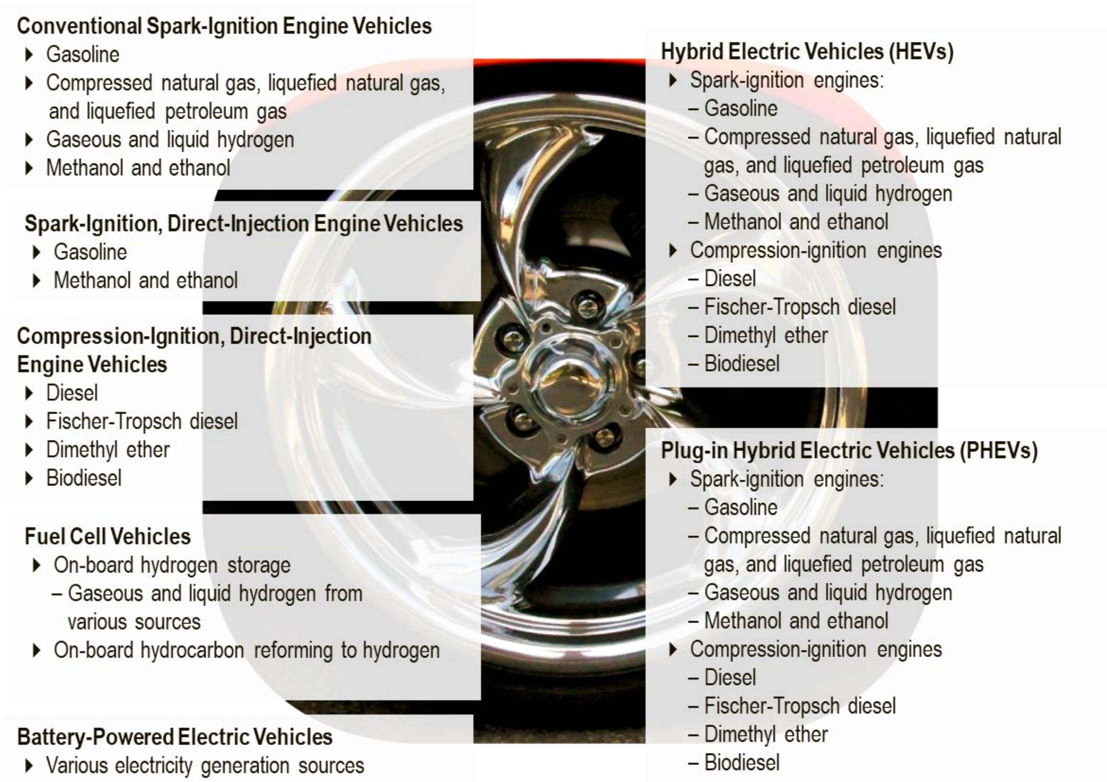

FIGURE 4 Vehicle Technologies for Road Transportation Included in GREET

TABLE 1 presents the vehicle classes and fuel/vehicle technology options included in GREET for medium- and heavy-duty vehicles. For light-duty vehicles, GREET includes passenger cars, sport utility vehicles (SUVs), and pickup trucks. Table 2 presents the aircraft classes in GREET for both passenger and freight air transportation. TABLE 3 presents the rail transportation modes in GREET, and TABLE 4 lists the marine fuels and vessel types included in GREET.

TABLE 1 Vehicle Classes and Fuel/Vehicle Technology Options Included in GREET for Heavy-Duty Vehicles

	BD	Ethanol	CNG	LPG	LNG, SI	LNG, DPI	DME	HHV	HEV	BEV	PHEV	FCEV
D. Class 8b LH Combination	x		x		x	x	x		x			x
D. Class 8b SH Combination	x		x		x	x	x		x			x
D. HD pickups and vans	x		x		x		x		x			x
D. HHD trucks	x		x		x		x		x			x

TABLE 1 (Cont.)

	BD	Ethanol	CNG	LPG	LNG, SI	LNG, DPI	DME	HHV	HEV	BEV	PHEV	FCEV
D. MHD trucks	x		x		x		x		x			x
D. LHD trucks	x		x		x		x		x			x
D. Refuse trucks	x		x		x		x	x	x	x		x
G. HD pickups and vans		x		x								x
G. MHD trucks		x		x								x
School buses	x		x		x		x		x			x
Transit buses	x		x		x		x		x	x		
Intercity buses	x		x		x		x					

BD = biodiesel; BEV = battery electric vehicle; CNG = compressed natural gas; DME = dimethyl ether; DPI = diesel pilot ignition; FCEV = fuel cell electric vehicle; HD = heavy-duty; HHD = heavy heavy-duty; HEV = hybrid electric vehicle; HHV = hybrid hydraulic vehicle; LH = Long Haul; LHD = light heavy-duty; LNG = liquefied natural gas; LPG = liquefied petroleum gas; MHD = medium-heavy duty; PHEV = plug-in hybrid electric vehicle; SH = Shor Haul; SI = spark-ignition.

TABLE 2 Aircraft Classes Included in GREET for Both Passenger and Freight Air Transportation

Aircraft Type	Aircraft Class
Passenger Aircraft	Single Aisle (SA) Small Twin Aisle (STA) Large Twin Aisle (LTA) Large Quad (LQ) Regional Jet (RJ) Business Jet (BJ)
Freight Aircraft	Single Aisle (SA-F) Small Twin Aisle (STA-F) Large Twin Aisle (LTA-F) Large Quad (LQ-F)

TABLE 3 Rail Classes and Fuel Options Included in GREET for Both Passenger and Freight Rail Transportation

	Diesel	Natural Gas	Electricity
Freight	x	x	
Passenger – intercity	x		x
Passenger – commuter	x		x
Passenger – transit			x

TABLE 4 Vessel Types and Fuel Options Included in GREET for Marine Transportation

	Diesel	Residual Oil	Bio-based Fuels
Large Container	x	x	x
Bulk Vessels	x	x	x
Tanker (crude carrier)	x	x	x

TABLE 5 lists the output attributes from GREET simulations. They include four general groups: energy use, greenhouse gas (GHG) emissions, criteria air pollutant emissions, and water consumption. As the table shows, energy use is further separated into different energy types; GHG emissions are aggregated with Inter-Governmental Panel on Climate Change (IPCC) global warming potentials (GWPs); criteria air emissions are separated into urban and total emissions (in the U.S. context); and water consumption is fresh consumptive water.

GREET LCA functional units include: per mile driven (for on-road passenger transportation); per ton-mile delivered (for freight transportation); per passenger-mile delivered (for passenger air transportation); per unit of energy produced and used (in million British thermal unit [Btu], megajoule [MJ], and gasoline gallon equivalent [GGE]); and per unit of feedstock (per ton of biomass used).

As for any other LCA models, data requirements for GREET development are extensive. Argonne has relied on these general data sources:

1. Open literature and research results from others;

2. Governmental databases, such as the Energy Information Administration's (EIA's) Annual Energy Outlook and the U.S. Environmental Protection Agency's (EPA's) e-Grid database; and

3. Argonne's own simulations, such as ASPEN Plus simulations for engineering processes, Autonomie simulations for vehicle fuel consumption, and EPA MOVES modeling of vehicle emissions.

Data sources and modeling approaches for GREET-specific technology options are documented in specific technical reports and journal articles available at the GREET web site.

TABLE 5 Output Attributes of GREET Simulations

Output Category	Output Items	Notes
Energy use		
	Petroleum (fossil)	
	Natural gas (fossil)	
	Coal (fossil)	
	Fossil energy	Including the three fossil energy types (petroleum, natural gas, coal)
	Total energy	Including the three fossil energy types and renewable energy (biomass, solar, wind, hydroelectricity, geothermal, and nuclear energy)
Greenhouse gases		GHGs are combined together with IPCC GWPs
	Carbon dioxide (CO_2)	
	Methane (CH_4)	
	Nitrous oxide (N_2O)	
	Black carbon	
	Albedo	Albedo GWP was estimated in an Argonne study
Criteria air pollutants		These emissions are separated into total emissions that occur everywhere and urban emissions that occur within U.S. urban areas (the latter is a subset of the former)
	Volatile organic compounds (VOCs)	
	Carbon monoxide (CO)	
	Nitrogen oxides (NO_x)	
	Sulfur oxides (SO_x)	
	Particulates measuring 10 micrometers or less in diameter (PM_{10})	
	Particulates measuring less than 2.5 micrometers in diameter (PM2.5)	
Water consumption		

2 MAJOR EXPANSIONS AND UPDATES IN GREET 2017

Major expansions and updates for GREET 2017 were undertaken in seven areas, as described in subsections 2.1 through 2.7.

2.1 BIOFUELS AND BIOPRODUCTS

To continue to enhance GREET LCA for various biofuel and bioproducts pathways, Argonne expanded the GREET model to include corn kernel fiber ethanol, biomass-derived high-octane gasoline, plastic-to-fuel, and woody-biomass-to-fuels pathways. Argonne also updated the Carbon Calculator for Land Use Change from Biomass (CCLUB) to include land use change (LUC) cases related to soybean biodiesel pathways and incorporated the Algae Process Description (APD), separated in previous GREET versions, within the GREET model.

2.1.1 Corn Kernel Fiber Ethanol

Argonne added new pathways for corn kernel fiber ethanol in corn ethanol plants. The new pathways can estimate life-cycle energy consumption, GHG emissions, and water use, for either combined ethanol (i.e., both starch ethanol and fiber ethanol) or separated ethanol (i.e., starch ethanol and fiber ethanol) types. Argonne re-evaluated two major coproducts, distillers' grains and solubles (DGS) and corn oil, generated during corn fiber separation in corn ethanol plants. Based on process engineering modeling and projections, both state of technology (SOT) and n^{th}-plant technology are analyzed in these pathways. Argonne is documenting these updates in a forthcoming journal article.

2.1.2 Biomass-Derived High-Octane Gasoline

Argonne completed LCA of two renewable hydrocarbon transportation fuels to examine the GHG emissions and water consumption impacts of production and use of such fuels: (1) renewable high-octane gasoline produced via indirect liquefaction of woody lignocellulosic biomass, and (2) renewable gasoline produced via fast pyrolysis of woody lignocellulosic biomass. These biofuel pathways are incorporated in GREET 2017. Detailed information on this GREET expansion is provided in a technical report entitled *Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Fast Pyrolysis, and Hydrothermal Liquefaction: Update of the 2016 State-of-Technology Cases and Design Cases* (available at: https://greet.es.anl.gov/publication-renewable_hc_2016_update).

2.1.3 Non-Recycled-Plastic-to-Fuel Pathways

These pathways describe the energy and environmental effects associated with converting non-recycled plastic (NRP) into ultra-low sulfur diesel (ULSD) fuel. Plastic-to-fuel (PTF) technology uses pyrolysis as the conversion technology. The LCA of PTF pathways includes feedstock properties, feedstock preparation, conversion of NRP into ULSD fuel, and combustion of final fuel in the vehicle. In addition, these PTF pathways provide different co-product allocation methods, including displacement, energy, and market allocation. Using different allocation methods allows the GREET user to decide (1) how to treat co-products (e.g., fuel gas and char), (2) which combustion technology to use for internal energy generation, and (3) which North American Electric Reliability Corporation (NERC) regions to select for the electricity grid. Argonne provides detailed information on this update in a *Science Direct* article entitled "Life-cycle analysis of fuels from post-use non-recycled plastics" (available at http://www.sciencedirect.com/science/article/pii/S0016236117304775?via%3Dihub).

2.1.4 Woody-Biomass-to-Fuels Pathways

Woody biomass biofuel production pathways, including carbon temporal effects, were added as a new worksheet called Woody in GREET 2017. Argonne considered three softwood and three hardwood species, focusing on forests in the Pacific Northwest, Southeastern, and Northeastern regions of the United States. Analysts considered carbon temporal effects using both the stand- and landscape-level approaches. For the stand-level approach, we present two carbon accounting methods: one considers the cumulative effects of carbon using a time-dependent GWP and the other evaluates carbon using a discount rate for future emissions. We also considered thermochemical conversion of biomass into renewable diesel and renewable gasoline for all species and additional pathways for biochemical conversion of hardwood species to ethanol. Detailed information on these updates will be provided in a forthcoming Argonne technical publication.

2.1.5 CCLUB

Argonne expanded CCLUB to estimate LUC emissions for soy biodiesel, incorporating four LUC cases and associated soil organic carbon (SOC) change updates related to soy biodiesel pathways. Argonne documented these expansions in a forthcoming journal article. For SOC modeling, the surrogate CENTURY model (SCSOC) was used to simulate SOC change associated with new land uses at the U.S. county level. Users can select other SOC data sources (i.e., Winrock, Woods Hole) for SOC change estimation. Argonne documented these expansions and updates in an updated technical report titled "*Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) – Users' Manual and Technical Documentation*," that is currently under review.

2.1.6 Algae Process Description

The APD, which was previously a standalone module linked to GREET, is incorporated into the Algae worksheet in GREET 2017. The model provides numerous biofuel production pathways for the various unit operations. For Renewable Diesel III production, users can select a process-level analysis, which uses the newly incorporated APD to determine material and energy flows, or a pathway-level analysis, which reflects biofuel production pathways determined by the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) for either the combined algal processing (CAP) or hydrothermal liquefaction (HTL) conversion methods. One production technology addition is the consideration of photobioreactors for cultivation. We considered four reactors that varied in terms of their design and production materials. These production methods can be used in conjunction with the pathway-level analyses. Argonne documented this expansion in a report titled *Greenhouse Gas Emissions, Energy and Water Use of Photobioreactors for Algal Cultivation and Biofuels Production* (available at https://greet.es.anl.gov/publication-algal_cultivation_biofuel).

2.2 HYDROGEN AND FUEL CELL VEHICLES

To continue to enhance GREET LCA for various hydrogen and fuel cell vehicle pathways, Argonne expanded the GREET model to include medium-duty and heavy-duty FCEV pathways. Argonne also incorporated several near-term hydrogen byproduct pathways from chlor-alkali plants into GREET 2017. The model also incorporated updates to emission factors of criteria air pollutant (combustion and non-combustion) emissions for steam methane reforming (SMR) hydrogen plants and for baseline petroleum refinery fuels.

2.2.1 Medium- and Heavy-Duty FCEVs

Argonne incorporated fuel cell electric medium- and heavy-duty vehicles (MHDVs) powered by gaseous hydrogen in GREET 2017. More specifically, FCEV technology was added for combination short-haul trucks, HHD vocational vehicles, MHD vocational vehicles, LHD vocational vehicles, HHD pickup trucks and vans, refuse trucks, and school buses. Representative U.S. average fuel efficiency ratios for fuel cell and conventional diesel MHDVs were developed using real-world idle fuel rates, Autonomie simulation results, EPA/National Highway Traffic Safety Administration (NHTSA) HD vehicle fuel efficiency standards, and county-by-county regional aggregation. Argonne will provide detailed information on these updates in a forthcoming journal article.

2.2.2 Byproduct Hydrogen from Chlor-Alkali Plants

Argonne added byproduct hydrogen pathways from chlor-alkali processes to GREET 2017 based on plant-by-plant data and regional aggregation. Chlor-alkali plants were divided into two groups: those with a combined heat and power (CHP) system and those without. To obtain the national average, we used production-weighted aggregation of CHP and non-CHP plants. For each of the three groups (CHP, non-CHP, and overall national average), we considered four different treatment strategies: venting, substitution, mass allocation, and market value allocation. The life-cycle inventory was built from an array of data collected from publicly available sources (e.g., EIA-923 forms, chlorine industry association booklets, technical reports from various organizations). Argonne will document these updates in detail in a forthcoming Argonne technical publication.

2.2.3 Refinery and SMR Criteria Pollutant Emissions

Refineries emit CAPs (VOC, CO, NO_x, SO_x, PM_{10}, and $PM_{2.5}$), along with GHGs, primarily via combustion of refinery fuels such as refinery still gas, refinery catalyst coke, natural gas, and other fuels. GREET 2017 provides updated CAP emissions from refinery processes for combustion sources; the updates are based on a recent research effort that focused on obtaining emission factors for two of the major refinery fuels: still gas and refinery catalyst coke. GREET 2017 also contains updated CAP emissions for hydrogen production from SMR plants on the basis of information is obtained from the 2014 National Emissions Inventory (NEI) database (the SMR hydrogen production information was obtained from various sources). Because refinery products and hydrogen produced via SMR are commonly used in other processes and pathways in GREET, the emissions factor updates for these fuels led to widespread changes in evaluating the CAPs in other products and pathways.

The CAP updates are documented in a report titled *Creation of Unit Process Data for Life Cycle Assessment of Steam Methane Reforming and Petroleum Refining* (available at https://greet.es.anl.gov/publication-air_pollutants_smr_petroleum).

2.3 ELECTRICITY AND ELECTRIC VEHICLES

Argonne expanded electricity generation pathways in GREET 2017 to include CHP generation and options for carbon capture and storage for fossil coal and natural gas plants. We also updated the generation efficiency CAP emission factors for integrated coal gasification combined-cycle (IGCC) power plants.

For BEVs, GREET 2017 was expanded to include life-cycle inventory (LCI) data for the production of $LiNi_{1}/3Mn_{1}/3Co_{1}/3O_{2}$ (NMC111), $LiNi_{0}.6Mn_{0}.2Co_{0}.2O_{2}$ (NMC622), $LiNi_{0}.8Mn_{0}.1Co_{0}.1O_{2}$ (NMC811), and recycled nickel-manganese-cobalt oxide (NMC) cathode materials. GREET 2017 also incorporates updated energy and water consumption for lithium-ion battery manufacturing and LCI data for $LiNi_{0}.4Mn_{0}.2Co_{0}.4O_{2}$ (NMC424) cathode material production.

2.3.1 CHP Generation Units

Argonne expanded GREET 2017 by adding several natural gas and coal CHP generation technologies, including natural gas steam turbine, natural gas combustion turbine, natural gas combined cycle, and coal steam turbine, using EIA power plant data from Form 923 (2015 data files). Detailed information on these expansions is provided in a technical memorandum titled *Addition of Combined Heat and Power Electricity Plants to the GREET® Model* (available at https://greet.es.anl.gov/publication-chp_add_2017).

2.3.2 CCS for Fossil Generation Units

GREET 2017 was expanded to include carbon capture and storage (CCS) options for natural gas-based and coal-based power generation technologies. The CCS options included integrated system designs and power-match auxiliary gas turbine CHP design. Detailed information on these expansions is provided in a technical memorandum titled *Analytical Models of Carbon Capture Plant Configurations in GREET* (available at https://greet.es.anl.gov/publication-ele_ccs_2017).

2.3.3 IGCC Power Plants

The generation efficiency and CAP emission factors of IGCC power plants were updated in GREET 2017 based on a 2015 study titled *Cost and Performance Baseline for Fossil Energy Plants Volume 1b: Bituminous Coal (IGCC) to Electricity* by the National Energy Technology Laboratory and Energy Sector Planning and Analysis. These updates are documented in a technical memorandum titled *Update on Generation Efficiency and Criteria Air Pollutant Emissions of Integrated Coal Gasification Combined Cycle Power Plant* (available at https://greet.es.anl.gov/publication-coal_igcc_2017).

2.3.4 Battery Materials and Manufacturing Energy

The GREET2 (vehicle-cycle) model includes an LCA module to characterize the material and energy consumption associated with production of automotive lithium-ion batteries. GREET 2017 incorporates new LCI data for the production of NMC111, NMC622, NMC811, and recycled NMC cathode materials. The 2017 release of GREET2 also includes updated energy and water consumption values for lithium-ion battery manufacturing and LCI data for NMC424 cathode material production. We obtained the information required for these updates through (1) site visits to two lithium-ion battery manufacturing facilities and one lithium-ion battery recycling facility in China; and (2) Argonne's latest modeling effort by Ahmed et al. to support efficient simulation, analysis, and design of advanced lithium-ion battery technologies. These updates reflect the current status of lithium NMC cathode material production and battery manufacturing. Detailed information on these expansions is provided in a technical memorandum titled *Update of Life Cycle Analysis of Lithium-ion Batteries in the GREET Model* (available at https://greet.es.anl.gov/publication-Li_battery_update_2017).

2.4 WATER CONSUMPTION FACTORS

Argonne developed distribution functions for water consumption factors and incorporated them in GREET 2017. The new GREET version also incorporates updated water consumption factors for shale gas and biodiesel pathways. The newly developed distribution functions are documented in a DOE program record titled *Water Consumption for Light-Duty Vehicles' Transportation Fuels* (available at https://www.hydrogen.energy.gov/pdfs/17005_water_consumption_ldv_fuels.pdf). The water consumption factors for shale gas production are documented in a journal article titled "Wells to wheels: Environmental implications of natural gas as a transportation fuel" by H. Cai, A. Burnham, R. Chen, and M. Wang, (*Energy Policy* 109, 565–578, 2017).

2.5 NATURAL GAS

Argonne conducted a WTW assessment of fresh water consumption, GHG emissions, and air emissions associated with using CNG and LNG as transportation fuels in three heavy-duty natural gas vehicle (NGV) types. We assessed fresh water consumption during NG production in major U.S. shale gas plays on the basis of recent reports and studies. Literature review of methane leakage from the NG supply chain and vehicle operation were used to improve the estimates of NGV GHG emissions. Assessment results show that NGVs could reduce freshwater consumption significantly and offer air emissions benefits compared with their heavy-duty diesel counterparts. WTW GHG emissions in NGVs are largely driven by the vehicle's powertrain efficiency, as well as methane leakage rates from both the NG supply chain and vehicle end use. The WTW GHG emissions of NGVs were estimated to be slightly higher than those of their diesel counterparts given the WTW methane leakage.

Argonne updated natural gas pathways in GREET1_2017 based on the work documented in above journal article in Section 2.4, which examined freshwater consumption associated with shale natural gas production and WTW NGV GHG emissions, NO_X, and PM emissions. A technical memorandum by A. Burnham titled *Updated Natural Gas Pathways in the GREET1_2017 Model* (available at https://greet.es.anl.gov/publication-ng_update_2017) provides supplemental information on upstream GHG emissions associated with natural gas production, processing, transmission, and distribution; methane leakage emissions from natural gas vehicle stations; and natural gas HDV methane leakage and NO_x emissions. The updates to natural gas pathways and natural gas vehicles are documented in detail in the above journal article in Section 2.4 and the Burnham memorandum.

2.6 WASTE TO ENERGY

Various waste-to-energy (WTE) conversion technologies can generate energy products from municipal solid waste (MSW). Accurately evaluating landfill gas (LFG) (mainly methane) emissions from base-case landfills is critical to conducting a WTE LCA of GHG emissions. To reduce uncertainties in estimating LFG emissions, Argonne updated the key parameters for its generation based on experimental results. Because WTE pathways typically use specific waste streams, it is important to obtain waste-component-specific LFG emissions. Thus, the fractions of degradable organic carbon dissimilated (DOC_F) of waste components (e.g., paper, wood, food waste, yard trimmings) were evaluated and updated in GREET 2017. The collected data and life cycle accounting improve the assessment of GHG impacts from landfills, which supports transparent decision-making regarding the sustainable treatment, management, and utilization of MSW. These updates are documented in a paper titled Evaluation of Landfill Gas Emissions from Municipal Solid Waste Landfills for the Life-Cycle Analysis of Waste-to-Energy Pathways (available at https://greet.es.anl.gov/publication-msw_to_energy_emis).

2.7 LOW-OCTANE FUEL

Gasoline compression ignition (GCI) engines using a low-octane gasoline-like fuel (LOF) have good potential to achieve lower NO_x and PM emissions with higher fuel efficiency (comparable to the modern diesel compression-ignition engines). Argonne conducted a WTW analysis of the GHG emissions and energy use associated with the potential LOF GCI vehicle technology. We modified a detailed linear programming model of the U.S. Petroleum Administration for Defense District Region (PADD) III refinery system — which produces more than 50% of U.S. refined products — to simulate the production of the LOF in petroleum refineries and provide product-specific energy efficiencies.

The LOF production pathway and corresponding vehicle technology of a GCI engine running on LOF were added to GREET 2017. Detailed information on these updates is available in a Society for Automotive Engineers technical paper titled *Well-to-Wheels Analysis of the Greenhouse Gas Emissions and Energy Use of Vehicles with Gasoline Compression Ignition Engines on Low Octane Gasoline-Like Fuel* (available at https://greet.es.anl.gov/publication-wtw-lof-gci).

3 OTHER UPDATES

Other updates to GREET 2017 include the three areas described in subsections 3.1 through 3.3.

3.1 SOYBEAN AND TALLOW BIODIESEL

GREET 2017 includes updated inventory data for soybean farming, soy oil extraction, and vegetable oil transesterification processes associated with the soybean biodiesel pathway. Argonne also updated processes for soy oil and soybean meal extraction for other uses. These updates are documented in a forthcoming journal article "Assessment of Life-Cycle Energy Consumption, Greenhouse Gas Emissions, and Induced Land Use Change Impact of U.S. Soy Biodiesel," that is currently under review. GREET 2017 also incorporated updated inventory data for tallow rendering and high free fatty acid oil transesterification processes associated with the tallow biodiesel pathway.

3.2 ELECTRICITY GENERATION MIX

Electricity generation pathways are commonly used in the various fuel production pathways in GREET. The energy and emissions intensities of electricity change over time and vary by region. Therefore, the mix of energy sources and technologies used for electricity generation is updated annually in GREET. In the GREET 2017 model, the electricity generation mixes of the United States, eight NERC regions, and two additional states (Alaska and Hawaii) are updated using the EIA's *Annual Energy Outlook 2017*.

3.3 LIGHT-DUTY VEHICLE MANUFACTURING

Stamping is an important sheet metal reforming process, especially for vehicle production. The 2017 release of GREET2 includes updates on the energy requirements and material efficiency for steel and aluminum stamping associated with vehicle production. Details of these updates are provided in a technical memorandum titled *Update of Process Energy Requirement and Material Efficiency for Steel and Al Stamping in the GREET Model* (available at https://greet.es.anl.gov/publication-steel_al_update_2017).

GREET 2017 also incorporates updated vehicle weight calculations that fix previous issues, especially for vehicles with large motive batteries. Finally, GREET 2017 includes updated lifetime vehicle driving distances, consistent with those calculated by the VISION model. Argonne documented these updates in a technical memorandum titled *Update of Vehicle Weights in the GREET® Model* (available at https://greet.es.anl.gov/publication-v_weight_update_2017).

4 DEFAULT WTW RESULTS OF KEY FUEL PATHWAYS AND TECHNOLOGY OPTIONS IN THE GREET 2017 WTW CALCULATOR

To provide a quick reference of key fuel pathways and technology options in the GREET 2017, Argonne has been developing a WTW Calculator each year based on newly released GREET versions. The WTW Calculator uses the default GREET parameters to develop GREET default WTW results (e.g., energy consumptions, GHG and CAP emissions, and water consumption). WTW Calculator 2017 includes fuel option results for ground and air transportation listed in TABLE 6. The GREET model, on the other hand, contains additional fuel pathway options and allows users to develop their own WTW estimates.

The WTW Calculator provides the results in two functional units: (1) energy functional units (such as per gge, per mmBtu, and per MJ) and (2) service functional units (such as per-mile and per-kilometer for passenger cars, and per-passenger-mile and per-passenger-kilometer for airplanes). With service functional units for passenger cars, the results are based on ICE technology, except for hydrogen and electricity, which are based on fuel cell and battery technologies, respectively.

TABLE 7 presents vehicle technology options in WTW Calculator 2017. In addition to ICE vehicles, three additional vehicle technologies for gasoline are available (HEV, PHEV10, and PHEV 40), which can be paired with U.S. average electricity generation mix or California (CA) average electricity generation mix. Once the functional unit and fuel pathway options are selected, clicking the “Generate Results” button creates a new spreadsheet with the tables and charts of the selected vehicle-fuel pathways. The download link and sample results of WTW Calculator 2017 are available at https://greet.es.anl.gov/results.

TABLE 6 Fuel Production Pathway Options in WTW Calculator 2017

Feedstock	Fuel
Petroleum Conventional Crude[a], Oil Sand[a], U.S. Average	Gasoline[b] Diesel Jet
U.S. Average Natural Gas	CNG LNG Gaseous Hydrogen[c] FTD FTJ Electricity[d] Combined Heat and Power[e]
North America Shale Gas Landfill Gas Manure-based Anaerobic Digestion Gas	CNG LNG
Corn Sugar Cane Switchgrass Miscanthus Willow Poplar Corn Stover Forest Residue	Ethanol[f]
Corn Stover Forest Residue	Renewable Gasoline[g] Renewable Diesel[g] Renewable Jet[h] Gaseous Hydrogen FTD FTJ
Coal	Gaseous Hydrogen[i] FTD[i] Electricity Combined Heat and Power[j]
Coal/Corn Stover[k] Coal/Forest Residue[k]	FTD
Soybean Palm Rapeseed Jatropha Camelina Algae Tallow[l]	BD[m] Renewable Diesel Renewable Jet[n]
Electricity U.S. Mix CA Mix Renewable	Electricity Gaseous Hydrogen[o]
Coke Oven Gas Byproduct from Chlor-Alkali Plants Landfill Gas[p] Manure-based Anaerobic Digestion Gas[p]	Gaseous Hydrogen

TABLE 6 (Cont.)

Feedstock	Fuel
Switchgrass Miscanthus Willow Poplar Forest Residue Geothermal	Electricity

[a] Conventional crude and oil sand options are only available for energy functional units.

[b] E0 and E10 results are available for energy functional units while only E10 results are available for service functional units.

[c] Via distributed steam methane reforming, central steam methane reforming (w/ and w/o carbon capture and sequestration [CCS]), and high temperature electrolysis with solid oxide electrolyser cell (SOEC)

[d] Via NG combined cycle (NGCC)

[e] Via NGCC without CCS and with CCS (integrated design and gas turbine auxiliary), NG boiler, and NG gas turbine

[f] Ethanol is E100 with energy functional units, but E85 with service functional units.

[g] Via pyrolysis.

[h] Synthesized iso-paraffinic via direct-sugar-to-hydrocarbon

[i] Via central gasification with and without carbon capture and sequestration.

[j] Via coal boiler without CCS and with CCS (integrated design and gas turbine auxiliary)

[k] 80% coal and 20% biomass by mass.

[l] Not available for renewable jet

[m] Biodiesel (BD) is B100 with energy functional units, but B20 with service functional units.

[n] Hydroprocessed esters and fatty acids

[o] Via distributed electrolysis.

[p] Via central steam methane reforming.

TABLE 7 Vehicle Technology Options in WTW Calculator 2017

Fuel	Vehicle Technology
Gasoline (E10)	ICEVs HEVs
Gasoline (E10) with Electricity (US mix and CA mix)	PHEVs 10 PHEVs 40
CNG, LNG Ethanol (E85) Petroleum Diesel FTD BD (B20) Renewable Gasoline and Diesel	ICEVs
Gaseous Hydrogen	FCEVs
Electricity	BEVs

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